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Analysis of power and frequency control requirements in view of increased decentralized production and market liberalization

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Abstract

This paper presents a systematic approach of the analysis of the minimum control requirements that are imposed on power producing units in the Netherlands, especially in the case when decentralized production increases. Also some effects of the liberalization on the control behavior are analyzed. First an overview is given of the amount and type of power production in the Netherlands, followed by a review of the control requirements. Next models are described, including a simplified model for the UCTE power system. The model was tested against frequency and power measurements after failure of a 558 MW production unit in the Netherlands. Agreement between measurements and model predictions proved to be good. The model was subsequently used to analyze the primary and secondary control requirements and the impact of an increase in decentralized power production on the fault restoration capabilities of the power system. Since the latter production units are not actively participating in primary and secondary control, fault restoration takes longer and becomes unacceptable when only 35% of the power producing units participate in secondary control. Finally, the model was used to study the impact of deregulation, especially the effect of “block scheduling”, on additional control actions of the secondary control. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Power transient; Frequency transient; Simplified model; Primary control; Secondary control; Deregulation; Block scheduling

1. Introduction

In the Netherlands about 70% of the electricity production is supplied by the large production companies. This is often called centralized power generation. About 30% is generated by decentralized or dispersed generation consisting of combined heat and power (chp), wind turbines, photo voltage, etc. In the years to come, decentralized generation will increase and constitute a larger part of the total electricity demand.

Control requirements are imposed on centralized and decentralized generation. The control requirements for centralized generation are more stringent than those for decentralized generation. By increasing decentralized generation it may be necessary to review the control requirements imposed on centralized and decentralized generation, in order to deal with power unbalance in a

fast and effective way. The situation can become even more pressing due to the liberalization of the electricity market. This paper will review the control requirements for these situations. First an overview of the power production will be given, followed by a description of the control strategy/requirements, a description of the simulation model, analysis and conclusions.

2. Power generation units

Table 1 gives a survey of the maximum available nominal power generation in the Netherlands. The table shows the units under secondary control separately. This controller will be explained in a later section.

After the Dutch Electricity Act of August 1998 came into force, power generation is divided into three classes: small contributors ($P_{\text{nominal}} < 5$ MW), medium sized contributors ($5 < P_{\text{nominal}} < 60$ MW) and large contributors ($P_{\text{nominal}} > 60$ MW). Table 2 shows power generation according to the new situation.

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Table 1

Overview of centralized and decentralized power generation capacity

Centralized power under secondary control	11190 MW	62.6%
Centralized power not under secondary control	1930 MW	10.8%
Decentralized power, $P < 5$ MW (exclusive agricultural sector)	80 MW	0.5%
Decentralized power, $5 \text{ MW} < P < 60$ MW	830 MW	4.6%
Decentralized power, $P > 60$ MW	3230 MW	18.1%
Power from waste	320 MW	1.8%
Wind turbines	290 MW	1.6%

Table 1

Table 2

Power generation capacity according to size of unit

Category	Total nominal power (MW)	Decentralized (MW)	Under secondary control (MW)
0 $P < 5$ MW ^a	80	80	
1 $5 < P < 60$ MW	1120	830	
2 $P > 60$ MW	16670	3230	11190

^a Exclusive agricultural heat and power installations.

3. Control strategy for power generation

In the normal situation there will be a balance between power production, load and power-exchange with neighboring countries. Due to disturbances, uncertainties in prognoses, an unbalance can exist, manifesting itself in a deviation of the frequency from its setpoint and a mismatch in the desired power exchange with neighboring countries. In order to ensure that the power production is controlled in a coordinated way, a control strategy with control requirements has been established by the UCTE ([Union pour la Coordination de la Transport de l'Electricity, 1998](#)). The control strategy consists of three types of control: primary control, secondary control and tertiary control.

A principle of the strategy is that all countries contribute to the elimination of a disturbance through primary control. This type of control is activated in the 0–30 s time frame and must be able to sustain for several minutes. This control action is locally installed on the unit level and is proportional to the frequency deviation.

Secondary control is used to eliminate the disturbance in the country where the disturbance occurred. This type of control is active during the time frame from 30 s to 15 min.

Tertiary control could be active, e.g. every 10 min and is used to create sufficient controllability for secondary control and calculates the economically optimal distribution of setpoints over the power generating units.

4. UCTE requirements

For every country participating in the UCTE power system, a minimum amount of primary power is

prescribed relative to the amount of power generation in respect to the total production of the UCTE; for the Netherlands this is 110 MW (for 1998). The total primary reserve power has to cope with a worst case disturbance in the power system of 3000 MW in such a way that no load need to be switched off (frequency does not drop below 49 Hz).

In order to realize the 110 MW, Sep (Dutch Board for Power Production) and EnergieNed (Dutch Board for Power Distribution) defined specifications which are given in [Table 3](#).

UCTE pose that after a disturbance in a particular country, secondary control should increase power to eliminate the disturbance within 15 min. The maximum rate of change of the secondary control is in the Netherlands 0.5% per minute of the nominal power output of the power plant.

5. Modeling assumptions

The complexity of a model depends on the objectives that have been set and the application of the model. In this case the objectives are to develop a simple model that is capable of quantitatively predicting maximum power and frequency changes on a power disturbance in the local power system and qualitatively predicting the power and frequency transients.

In the literature much attention has been paid to modeling of power plants and systems, e.g. ([Welfonder, Lampert, & Heilemann, 1980](#); [Colombo, De Marco, Ferrari, & Magnani, 1983](#)). Also detailed software tools are available (e.g., PSS/E). However, for this study a simplified model was found to be adequate enough to study the most important dynamic characteristics: power exchange transients and frequency transients under changing conditions and the impact of primary and secondary control. In view of the modeling objectives, a simplified semi-empirical model was developed in Simulink/ Matlab using the following assumptions:

- the law of conservation of energy has been applied to the active power balance,
- only phenomena which impact the power balance have been modeled,

Table 3
Primary control requirements (1998)

	Maximum primary reserve contribution (%)	Droop (see Eq. (5)) (%)	Maximum allowable dead band (mHz)
$5 < P_{\text{nominal}} < 60$ MW	8	max 10	150
$P_{\text{nominal}} > 60$ MW	1	4	0

- voltage control is considered decoupled from active power control,
- it is assumed that no voltage problems occur,
- transport limitations are not considered,
- only units of the Netherlands with nominal power > 5 MW will be modeled explicitly.

6. Model of a power plant

A standard model has been developed which can be applied for several types of power plants. For the standard model the following parameters can be adjusted:

- minimum produced power,
- maximum produced power,
- initially produced power,
- maximum speed of power changes $|dP/dt|$,
- dominant time constants, inclusive parameters concerning delay of response,
- primary control parameters: dead band, droop.

The dynamics of the model consists of two parts:

- fast model part for the primary reserve activation,
- slow model part for the secondary reserve activation.

The model equation applied for the fast action is not extracted from literature, but developed by matching a mathematical equation on a realistic response. The equation consists of a low and a high pass filter in series:

$$\frac{\Delta P}{\Delta P_{\text{set}}} = \frac{\tau_H s}{\tau_H s + 1} \frac{K}{\tau_L s + 1}. \quad (1)$$

It represents the relationship between a change of produced power and a change in power setpoint. In our model for gas fired units $\tau_H = 25$ s, $\tau_L = 12.5$ s, $K = 1.5$ were used and for coal fired units $\tau_H = 85$ s, $\tau_L = 10.0$ s, $K = 1.2$. The step response of this filter combination is shown as curve a in Fig. 1.

For the long-term production of additional power, more fuel will have to be supplied to the boiler in order to produce more steam (in the case of a steam turbine).

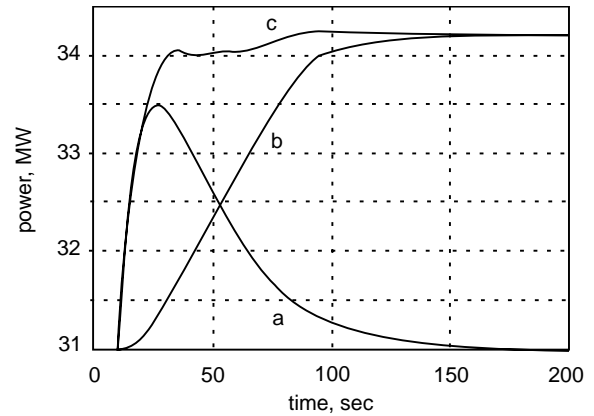


Fig. 1. Response of a gas-fired unit on a step change in power demand. a, response primary action; b, response fuel increase; c, total power response.

The model, representing the relatively slow power changes, can be approximated by

$$\frac{\Delta P}{\Delta P_{\text{set}}} = \frac{e^{-\theta s}}{\tau s + 1}. \quad (2)$$

This model is characterized by a dead time θ and time constant τ and results in an S-shaped response curve (b, Fig. 1). The following average values were found to give a good approximation of the response: for an oil or gas fired unit $\theta = 10$ s and $\tau = 17$ s; for a coal fired unit $\theta = 30$ s and $\tau = 60$ s. The combined response is curve c.

All the productions units in the Netherlands are modeled with this standard model and coupled to the grid model. The parameters were tuned with help of experimental data.

7. Grid modeling

For the model of the grid the energy balance was applied, Fig. 2.

When the load is larger than the generated power, the frequency will decrease. The value of K_{net} depends on the inertia of the rotors and is inversely proportional to it. It also depends on the load. The value of K_{net} is estimated from frequency-time responses after failure of a production unit.

8. UCTE-grid

The following countries have been included in the simulation study: the Netherlands, Belgium, Luxembourg, France, Germany, Spain, Portugal, Italy, Switzerland, Austria, Poland, the Czech Republic, Slovakia and Hungary. These countries have been grouped by a number of clusters and between adjacent clusters power exchange has been modeled as shown in Fig. 3.

Each cluster is modeled as one large energy producer with its own primary control, a constant load and a grid model according to Fig. 2. Secondary control is not modeled in foreign countries. In principle the secondary control of foreign countries should not be active due to unbalance in the Netherlands.

For the clusters the values of K_{net} as shown in Table 4 have been applied.

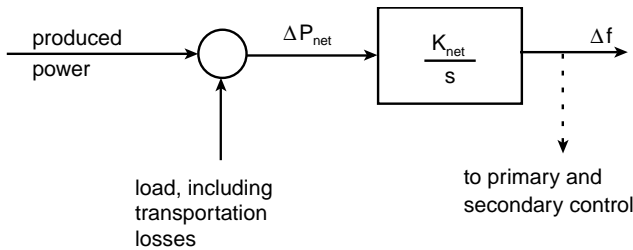


Fig. 2. Grid model (s = Laplace operator).

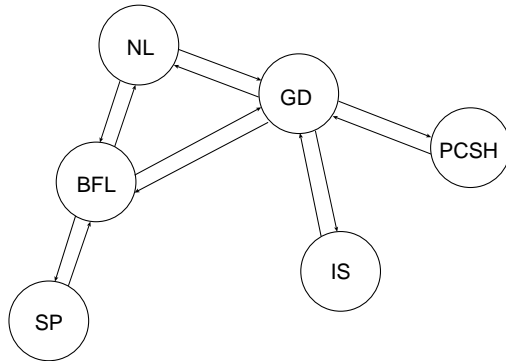


Fig. 3. Modeled power exchange between clusters.

Table 4
Estimated values of the gain of the power system

Country	K_{net} (Hz/MW)
The Netherlands (NL)	1.0E-4
Germany and Denmark (GD)	1.0E-5
Italy and Switzerland (IS)	2.0E-5
Belgium, France and Luxembourg (BFL)	1.5E-5
Spain and Portugal (SP)	3.5E-5
Poland, Czech republic, Slovakia, Hungary (PCSH)	2.7E-5

The power exchange between the clusters can be given by (Anderson & Fouad, 1977):

$$\delta = \int 2\pi \Delta f dt, \quad (3)$$

$$P_{ij} = P_m \sin(\delta_i - \delta_j) \quad (4)$$

in which δ is the load angle, Δf the frequency deviation from 50 Hz, P_{ij} the exchanged power between cluster i and j , MWe, and P_m equal to 3500 MW and is assumed to be constant.

The value of P_m has a significant impact on the frequency oscillations and the speed of power exchange between the clusters. The value has been tuned in such a way that realistic responses for the oscillations and power exchange were obtained.

9. Model of primary control

Primary control of the power unit is described by the following equation:

$$\frac{\Delta P}{P_{\text{nom}}} = \frac{100}{x} \frac{\Delta f}{f_{\text{nom}}} \quad (5)$$

in which Δf is the change in frequency in Hz, f_{nom} the nominal frequency (= 50 Hz), ΔP the change in power in MW, P_{nom} the nominal power in MW and x the droop or statism in %.

10. Model of secondary control

A schematic of the secondary control structure is shown in Fig. 4. The input signals to the secondary control structure are the frequency f and the power exchange between the Netherlands and other clusters, P_{telines} . They are compared with their setpoints. The frequency deviation df is multiplied by the net droop and summed with dP_{telines} resulting in the area control error (ACE). The area control error is a measure of the unbalance between power production and demand. After filtering, proportional and integral action are calculated and summed (processed area control error, PACE). PACE is spread out over the units under secondary control according to a participation factor which is related to the nominal power of the unit. Subsequently the PACE signal is to be added to the economic base point signal (EPB), thus determining the power setting for each unit.

11. Validation of the proposed model

The model was tested using experimental data. The results of one test are shown in this paper: the response

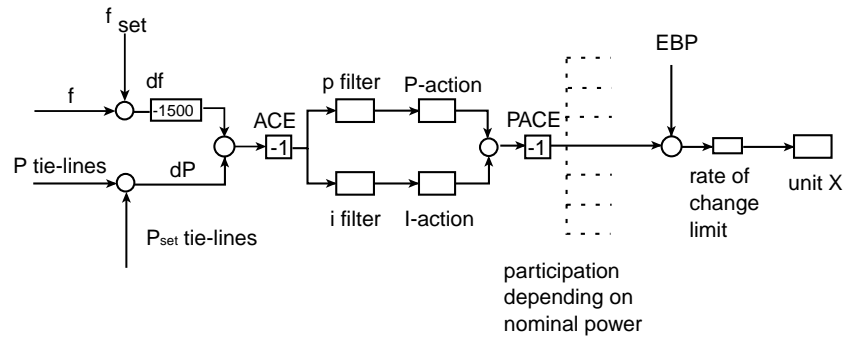


Fig. 4. Secondary control for a cluster of units.

of frequency and power exchange on a loss of production of 558 MW in the Netherlands. The total amount of produced power was 10325 MW. In Figs. 5 and 6 the results of power import and frequency are shown. Power import increased immediately (within 2 s) to a new value and the model corresponds to reality. The model shows a stronger oscillatory behavior than the measurements. These oscillations are due to the fact that individual parts of the system carry out movements against each other, for details see, amongst others (Spanner, Welfonder, Tillmann, & Jerényi, 1998). It should be remarked that the amplitude of the oscillation strongly depends on the measurement location and the real damping behavior of the power system.

The discrepancy in oscillating behavior between measurements and model will not affect the conclusions, and therefore no improvement in model response was required.

The frequency drops maximal 25 mHz within 25 s. This phenomena is important in our analysis.

It can be concluded that the main phenomena are present in our model for analyzing the primary and secondary control actions.

12. Analysis

In our analysis first the requirements for primary control will be examined. As said before the Netherlands must produce minimal 110 MW in the case of a disturbance of 3000 MW. For the realization of the 110 MW in the Netherlands, it is posed that all units above 60 MW should have a reserve of 1% at full load. Below 95% load, the unit can deliver up to 5% (not a requirement). The disturbance of 3000 MW will cause a frequency deviation of about 80 mHz at high load and about 180 mHz at low loads. Thus for the high load situation, 110 MW must be present at the high and the low load situation. In Table 5 the available primary reserve for the Netherlands is shown. For this calculation Eq. (5) has been used, the primary control requirements and information of Table 2.

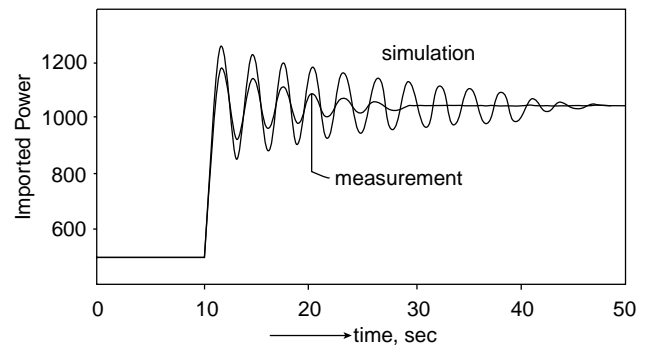


Fig. 5. Imported power response after a power failure of 558 MW.

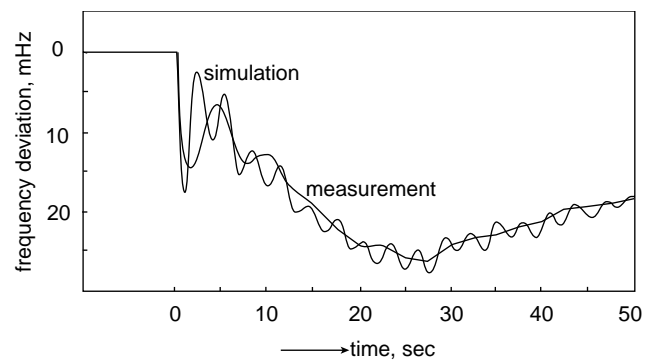


Fig. 6. Frequency response transient after a power failure of 558 MW.

In a high load situation, it is assumed that 71% of the central production operate at 99% and that 29% operate at 95% or below. Thus for the units at 99%, there is 1% available for primary reserve and for the units operating below 95% it is assumed that 5% will be available. This results in a primary reserve of 290 MW at high loads and the UCTE requirement can easily be met.

In the low load situation it was assumed that 20% of the production units were operating at 99% and 80% below 95%. At low loads the UCTE requirements can also be met. It is remarked that in this situation it is assumed that the contribution of the units operating

Table 5
Contribution to primary action

Production class	High load		Low load	
	Pn at operation point	Max contribution at $\Delta f = 80$ mHz (high load)	Pn at operation point	Max contribution at $\Delta f = 180$ mHz (low load)
$P_{nom} < 5$ MW	80	0	33	0
$5 < P_{nom} < 60$ MW	1089	0	436	16
$P_{nom} > 60$ MW	15531	110 (1%)	6231	12 (1%)
	71% at $P = 99\%$	180 (5%)	20% at $P = 99\%$	249 (5%)
	29% at $P < 95\%$		80% at $P < 95\%$	
Total (MW)	16700	290	6700	277

Table 6
Percentage of nominal power participation in secondary control

Case	Nominal power in production (MW)	Percentage of power under secondary control	Nominal power under secondary control
a	9702	81	7859
b	9702	60	5821
c	9702	36	3493

below 95% is 5% which is probably not true for all the units. A large margin is present to take care of this effect. Therefore it can be concluded that an increase of dispersed operation will not yet be a problem for the primary control given the current requirements. A large margin with respect to the 110 MW reserve is present in both the high and low load situation.

13. Secondary control action

Mid 1998, none of the ‘decentralized’ power producers were participating in secondary control. As their share of the total power production increases, a situation might arise that they have to participate in secondary control in order to be able to realize the UCTE requirement (fault restoration within 15 min). In this paragraph this sensitivity is analyzed.

Mid 1998, 62.6% of the total power production was under secondary control. A number of simulations were performed, with different percentages of nominal power under secondary control (Table 6). For these investigations again an outage of 558 MW has been considered. The results are given in Figs. 7 and 8. In the simulation model the current settings of the secondary control were applied including a 1.5% per min power ramp restriction.

As can be seen, there is no problem in case b, which corresponds closely to the current case. In the case of a 36% participation (case c), the response is too slow. It

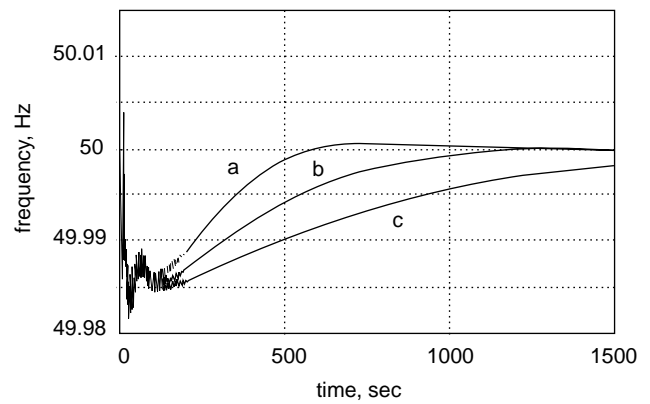


Fig. 7. Impact of percentage power under secondary control on frequency restoration, cases as shown in Table 6.

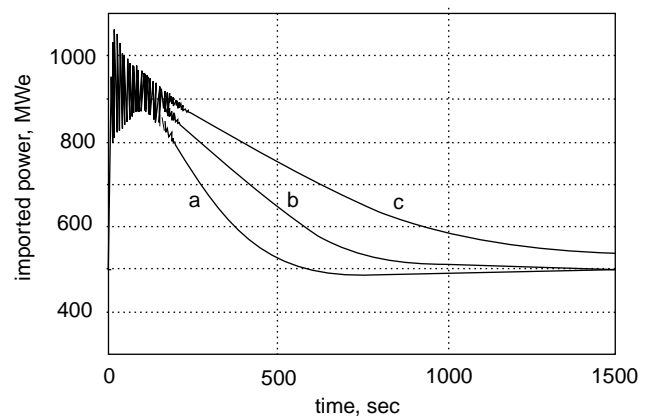


Fig. 8. Impact of percentage power under secondary control on imported power, cases as shown in Table 6.

may still be possible to achieve a somewhat better response through different controller tuning. However, it can be concluded that if the participation factor drops below 35%, there may be a problem in the fault restoration within 15 min. The oscillations occurring in Figs. 7 and 8 at the beginning of the simulation are caused by the simplicity of the model.

14. Liberalization

As a result of the liberalization there are the following market players in the Netherlands: power generation companies, industrial companies, suppliers, traders, customers. Energy is traded by means of bilateral contracts and/or via the Amsterdam Power Exchange (APX). A market player can be a Program Responsible party (PR). A Program Responsible party is responsible to realize its committed amount of energy (supply or consumptions). If a party will not be able to realize its committed amount of energy, it will be accounted for its unbalance. With help of the so-called E(nergy)-programs, the energy that a party will supply or consume, is defined. The E-program defines an average value of MWh to be produced in a program time unit (ptu). The program time unit in 1998 is 1 h.

With this setup, the average amount of energy within 1 ptu will be in balance, but within 1 ptu a momentary unbalance can occur. The production curve within the ptu can be chosen freely, e.g. like “block” shape, while the load is normally gradual. This results in momentary imbalance and requires secondary control actions. The amount of secondary control actions for $\text{ptu} = 1 \text{ h}$ is analyzed in this study. It is assumed that the load is gradual, curve d of Fig. 9. For the production a block shape is assumed (curve a), a power increase of 1000 MW production change in 20 min (b) and a power increase of 1000 MW production change in 60 min (c). Curve b is a realistic scenario for a certain situation as given in Table 7.

The unbalance between load and production is shown in Fig. 10. The largest unbalance between production and demand occurs at the hour crossings.

The error must be minimal in order to avoid unnecessary control actions. The stepwise production change is not realistic but is an indication of the maximum possible error. The load following error (ACE) varies between -200 and $+800$ MW. The load following error varies between -400 and $+200$ MW in

case b ($\Delta 1000 \text{ MW}$ change in 20 min). In the case c ($\Delta 1000 \text{ MW}$ change in 60 min) it is constant and is not shown in Fig. 10.

With the model the control actions of the secondary control have been studied for case a and b. In Figs. 11–13 the behavior of frequency, power exchange and required control actions are shown.

The maximum frequency change is about $+38 \text{ mHz}$ for a stepwise production change and $+8 \text{ mHz}$ for a rampwise production change. The power unbalance has more impact on the magnitude of the power import, Fig. 12. When stepwise production adjustments occur the import changes maximal 1300 MW (peak to peak). The import is a good measure for unbalance.

For rampwise production case the peak to peak change is 300 MW. Thus in this case the secondary control is able to reduce the unbalance from 600 (Fig. 10) to 300 MW. Fig. 13 shows the actions of the secondary control signal.

Table 7
Arbitrary example of power adjustment of production resources

P_{nominal} (MW)	ΔP reserve (MW)	dP/dt (%/min)	ΔP (MW/min)
600	250	1	6
500	200	2	10
400	150	1	4
250	100	3	7.5
250	100	2	5
120	40	2.5	3
100	30	3	3
100	30	5	5
80	40	2	1.6
50	20	5	2.5
50	20	4	2
50	20	2	1
Total 2550	1000		50.6

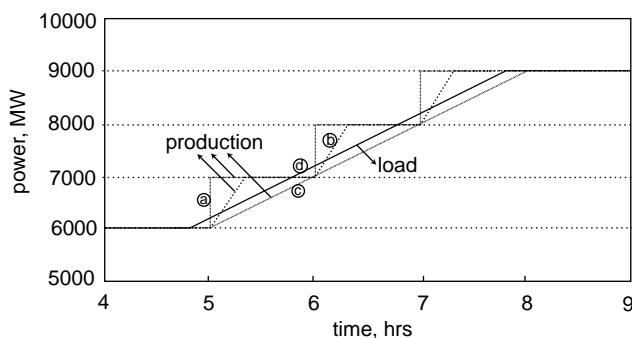


Fig. 9. Load following: load (d), stepwise production adjustment (a), ramp adjustment 1000 MW in 20 min (b), ramp adjustment 1000 MW in 60 min (c).

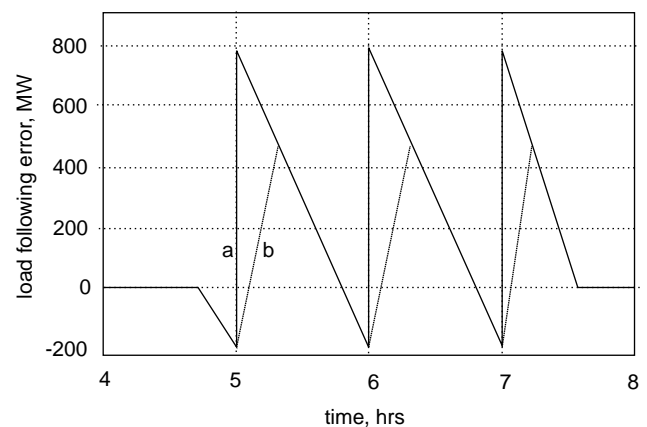


Fig. 10. Unbalance between load and production, MW, (a) stepwise production change, (b) rampwise production change.

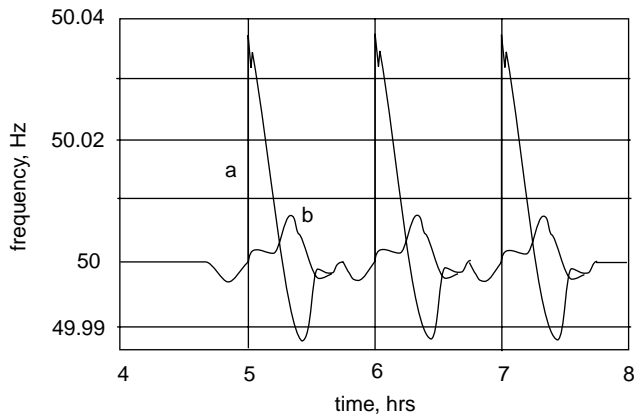


Fig. 11. Frequency transient during stepwise production change (a) and rampwise change of 1000 MW in 20 min (b).

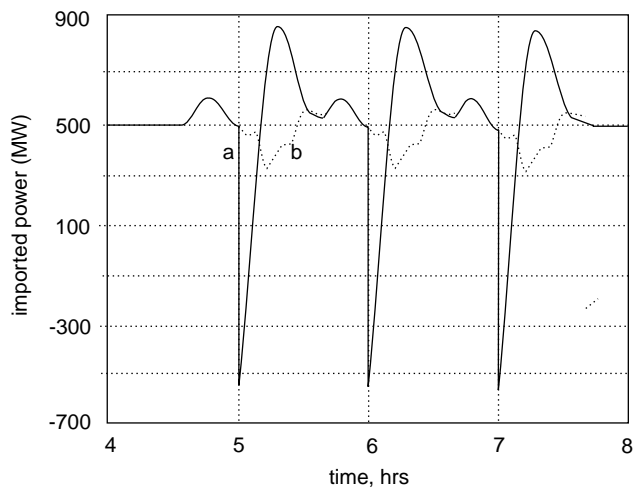


Fig. 12. Power import transient during stepwise production adjustment (a) and rampwise production adjustment (b).

The simulations show that this kind of unbalance has a major impact on secondary control actions, which is not economical.

There are a number of solutions to this problem. First, the program time unit can be reduced from once every hour to a shorter time period. One other solution could be a more gradual realization of the production corresponding to the load curve.

15. Conclusions

With a relatively simple model it was possible to analyze the control behavior in the case where decentralized power generation has increased in the Netherlands. The increase of decentralized power generation will not yet be a problem for the primary control action. A large margin with respect to the UCTE requirements

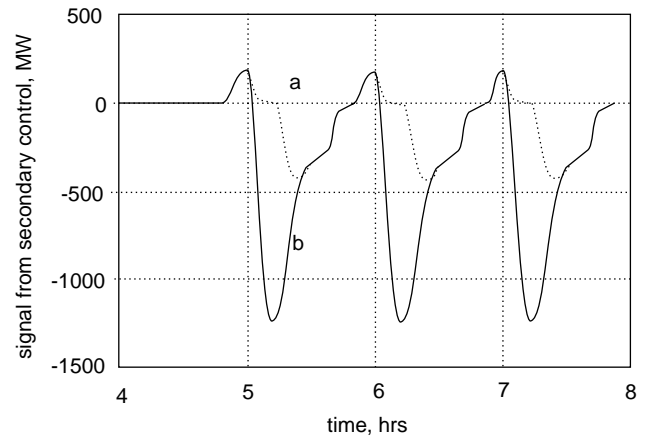


Fig. 13. PACE-signal from secondary control, for stepwise production adjustment (a) and rampwise production adjustment (b), 1000 MW in 20 min.

for the Netherlands is present. With respect to the secondary control it can be concluded that if the units that are participating to secondary control is less than 35% of the total production capacity of the Netherlands, problems can arise in the realization of the secondary control requirement. In 1998, the participation is about 60%, and therefore problems will not yet occur.

In addition, also the impact of some issues caused by the liberalization in the Netherlands was studied. Program Responsibility and E-programs are crucial tools in the liberalized structure to control the average amount of energy in 1 program time unit (= 1 h in 1998). However due to this strategy a momentary imbalance can occur within 1 h, because of the non-load conform behavior of production (block scheduling). The simulation study did show that especially at the hour crossings momentary imbalance can be high, which results in unnecessary secondary control actions, which is not economical.

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